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PYROPHYLLITIZATION, PINITIZATION, AND SILICIFICATION OF ROCKS AROUND CONCEPTION BAY, NEWFOUNDLAND

A. F. BUDDINGTON
Princeton University

INTRODUCTION

This paper embodies the results of a study of the regional and local alterations which have affected a series of volcanic rocks lying around the borders of the head of Conception Bay, on the Avalon Peninsula of Newfoundland. The field work was accomplished by the writer as a member of the Princeton Geological Expedition in Newfoundland during the summers of 1913 and 1914, in connection with a general study of the pre-Cambrian rocks of this region. The writer is indebted to the Geology Department of Princeton University for facilities for studying these rocks in the field and laboratory; to Dr. C. H. Smyth for supervision in the preparation of the report; to Professor G. Van Ingen for the photographs with which this paper is illustrated and for his interest in the work. The numbers used in this report refer to specimens deposited in the museum of Princeton University.

LOCATION

Regional alterations, such as silicification and chloritization, have affected the volcanic series wherever they outcrop, either in the area here under consideration (Fig. 1), or at other points to the north, such as Clarenville on Trinity Bay or Goose Arm on Bonavista Bay. The local alterations, comprising pyrophyllitization and pinitization, have affected the volcanics only in limited areas; the former being exhibited in a long narrow strip of rocks south of Manuels and the latter in outcrops to the north of the monzonite stock at Woodfords and in minute amounts associated with the pyrophyllite rocks at Manuels.

STRUCTURE

The volcanic series forms the lowest member of the Algonkian rocks in this region and has been mapped as Huronian by Howley (1907). The volcanics at the head of Conception Bay outcrop on the core of a major anticline, the eastern limb of which has been intruded by a huge batholith of granite. On the west side of Holyrood Bay they are also intruded by a stock of monzonite. The rocks are in addition excessively disturbed by profound and intensive faulting, and usually dip steeply.

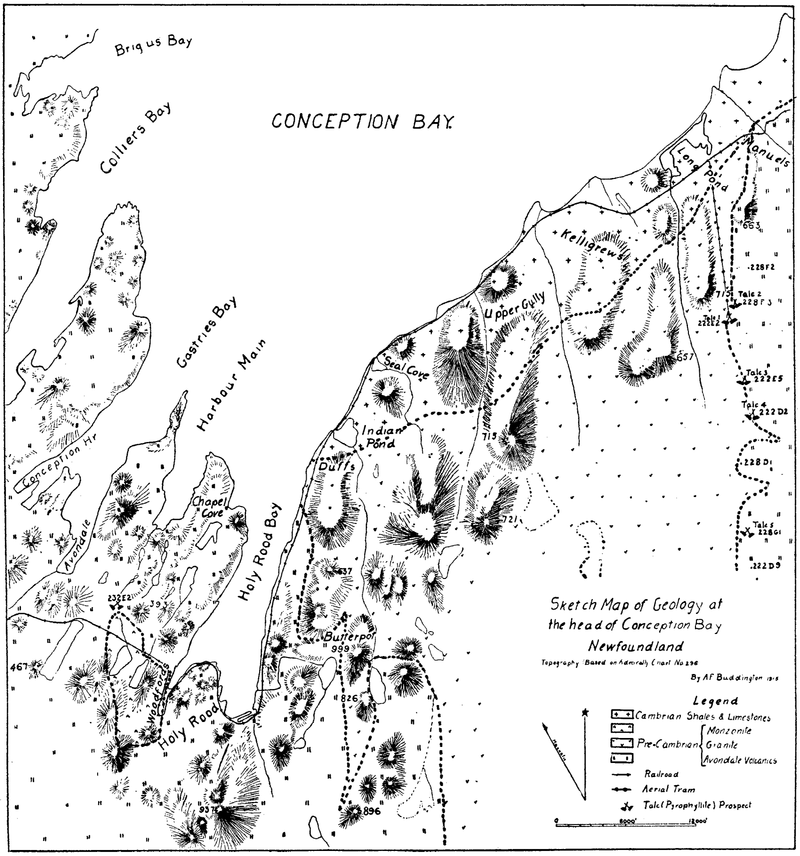


FIG. 1.

There is a strong probability that the line of contact between the granite and volcanics at Manuels marks the approximate locus of a fault zone. For at talc prospects 3, 4, and 5 the volcanics are faulted against either granite or green slate beds, and at prospect 3 the granite adjacent to the fault plane is silicified and pyritized and the rhyolite is silicified and carries traces of pyrophyllite. The pyrophyllite veins in turn are offset by small cross-faults.

CHARACTER OF VOLCANIC SERIES

The volcanics comprise a thick series of rhyolite and basalt flows with corresponding interbedded breccias, crystal tuffs, and tuffs, and a minor amount of waterworn material. The evidence with respect to their origin all points to their having accumulated under subaerial conditions.

TOPOGRAPHY

The topography developed on the volcanics at Manuels is that of a long, narrow, more or less barren plateau about 600 feet above sea-level. The volcanics at the head of Conception Bay are carved into a series of rugged isolated hills or ridges with differential elevations of from 200 to 1,000 feet. Glaciation during the Pleistocene period had a marked effect on the superficial features of the country, and many of the outcrops were scraped and polished by this agency.

WALL ROCKS OF THE PYROPHYLLITE VEINS

The pyrophyllite is confined almost exclusively to the rhyolite flows. Occasionally, however, pockets are found in the rhyolite breccias and conglomerates, but none at all occurs in any of the other rocks. The rhyolite flows exhibit three characteristic structures: flow or banded, spherulitic, and elliptical or lenticular. The spherulites may range in size from micro-spherulites visible only with the high powers of the microscope to huge spheroids as big as a man's head or even larger. They are usually more or less replaced by quartz of chalcedony. The elliptical structure has been called such because of its appearance on the weathered surface of the rock, where it shows as an assemblage of rude ellipses, or as lenses surrounded by a more or less schistose material which may be pyrophyllitized (Fig. 2). The ellipses vary from several inches to a foot in the direction of their longest axis. At talc prospect 5 a rhyolite showing this structure also contains scattered spherulites. This structure is characteristic of the white rhyolites of this area and may owe its origin to primary flowage phenomena, or to secondary dynamic forces, or probably to the former accentuated by the latter.

DESCRIPTION OF PYROPHYLLITE

The pyrophyllite veins are of such an extent that they attracted attention as a source of talc; many prospects were opened in the deposits and a 2½-mile aerial tram was built to the nearest mine. But, owing probably to the difficulty in separating the pyrophyllite from the admixed quartzose nodules, all work has been abandoned since 1904.

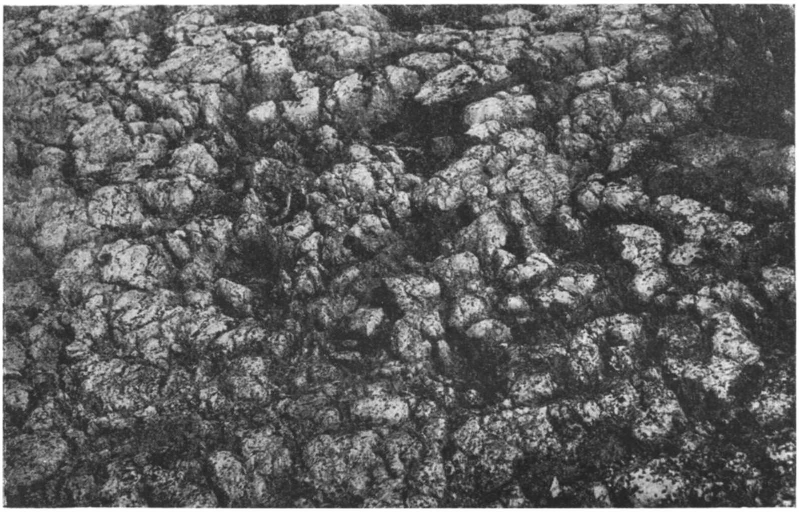


FIG. 2.—Lenticular structure in rhyolite. The material surrounding the more massive portions is partially pyrophyllitized.

The pyrophyllite where it replaces rhyolite flows, as it does almost exclusively, is a soft cryptocrystalline, light greenish-yellow rock with a waxy luster and a good cleavage parallel to the schistosity. In one case where it replaces the matrix of a volcanic conglomerate it is a light brown and in another where it replaces the matrix of a volcanic breccia it is cream colored.

The pyrophyllite may occur either as single well-defined veins, or as a series of veins, pockets, and lenticels, which together constitute what may be called a pyrophyllitic zone.

The former character is illustrated at talc prospect 5, where the pyrophyllite forms a vein about 500 feet long and varying from 6 to 15 feet in width in a white, densely spherulitic rhyolite. Near the one end of the vein which is exposed the pyrophyllite is full of nodules and stringers of the rhyolite, but becomes almost clear pyrophyllite in its central portion.

The latter character (pyrophyllitic zone) may be illustrated by the character of the pyrophyllite deposits at talc prospects 1 and 2. The country rock of the pyrophyllitic zones may be so altered as to constitute a quartz-pyrophyllite schist consisting of microcrystalline quartz and pyrophyllite, as at talc prospect 1, or it may be partially pyrophyllitized, as at talc prospect 2, or relatively unaltered as at talc prospect 4.

At talc prospect 1 large masses of pyrophyllite occur in pockets from 1 to 15 feet in diameter containing more or less country rock, or as thin sheets incasing lenses of quartz-pyrophyllite rock oriented parallel to the cleavage. It frequently occurs as an interlacing network of films veneering lenses of the quartz-pyrophyllite rock or as lenticels replacing the matrix between adjacent quartzose nodules. The pyrophyllite (222 *E* 2 *f* *x*) usually serves simply as a matrix for these nodules varying from a fraction of an inch to several feet in diameter, and even hand specimens are infrequent which do not contain one or more of them. Ramifying stringers of country rock may wander aimlessly through the pyrophyllite (Fig. 3) and veins of pyrophyllite reticulate in the country rock. It is quite possible that the nodular structure originated through the total replacement by pyrophyllite of the sheared zones between lenses of a rhyolite like that shown in Fig. 2, and the alteration of the lenses themselves to a quartz-pyrophyllite rock. On the west side of the talc mine here small pockets of cream-colored pyrophyllite, weathering green or yellow, are found replacing the matrix of a very coarse rhyolite breccia.

At talc prospect 2 there is a pyrophyllite zone about 30 feet wide in which pyrophyllite constitutes from a small percentage to one-half of the rock. Paralleling this zone at a distance of about 20 feet is a pyrophyllite vein 18 feet in width with a 3-foot stringer and many spheroids of altered rhyolite wall rock in its central portion. The spheroids vary from an inch to a foot in diameter, but average about 4 inches. A lenticular or elliptical structure (Fig. 2) characterizes the rhyolite adjacent to the vein and the schistose matrix of the lenses or ellipsoids is partially pyrophyllitized. A few hundred feet north of here a light brownish pyrophyllite is found replacing portions of the matrix of a white rhyolite conglomerate.

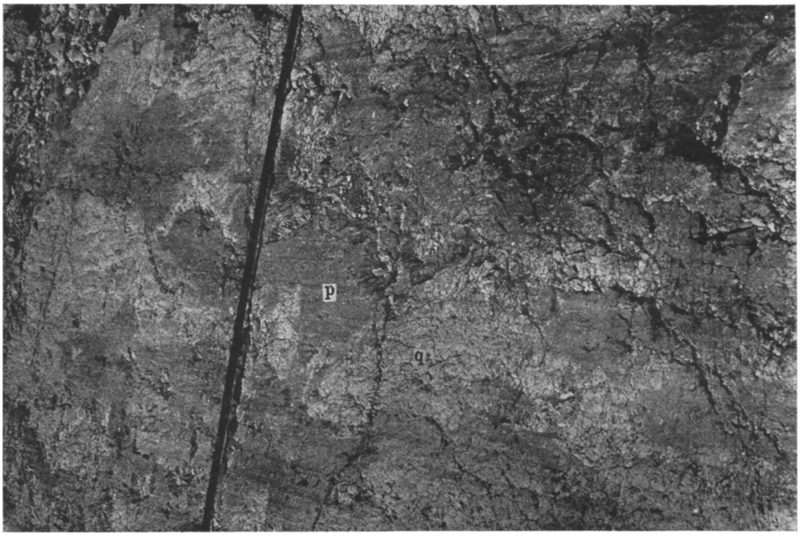


FIG. 3.—View of portion of pyrophyllite vein, showing intermingling of pyrophyllite and country rock. *p* = pyrophyllite; *q* = quartz-pyrophyllite.

DESCRIPTION OF PINITE

At Manuels the pinite is a relatively rare constituent and is interesting only from the viewpoint of its origin. It is best exhibited at talc prospect 5 and at a point marked 228 *D* 1 on the map. Fig. 4 is a photograph taken at this latter locality and represents the matrix of a spherulitic rhyolite (228 *D* 1 *h*) replaced by dark-colored pinite. The spherulites here average about 1 inch in diameter and are so intermingled with smaller ones as to make up almost the entire bulk of the rock. The pinitized groundmass possesses a waxy luster, dark dirty-green in color, and is quite soft. The parting of the pinite is in general parallel to the cleavage of the rhyolite, although in detail it is a series of curving shell-like scales, owing to its parting following the circumference of the more resistant spherulites. An analysis of this matrix is given in this *Journal* on p. 137 (No. 7). Very rarely pinite is found along the original contraction cracks of the spherulites or at the heart of a spherulite. Patches, lenticels, and minute veins of pinite are found throughout the rhyolite flows and agglomerates, often replacing the matrix of spherulitic zones (228 *G* 1 *k*) or certain flow lines (222 *E* 2 *x*).

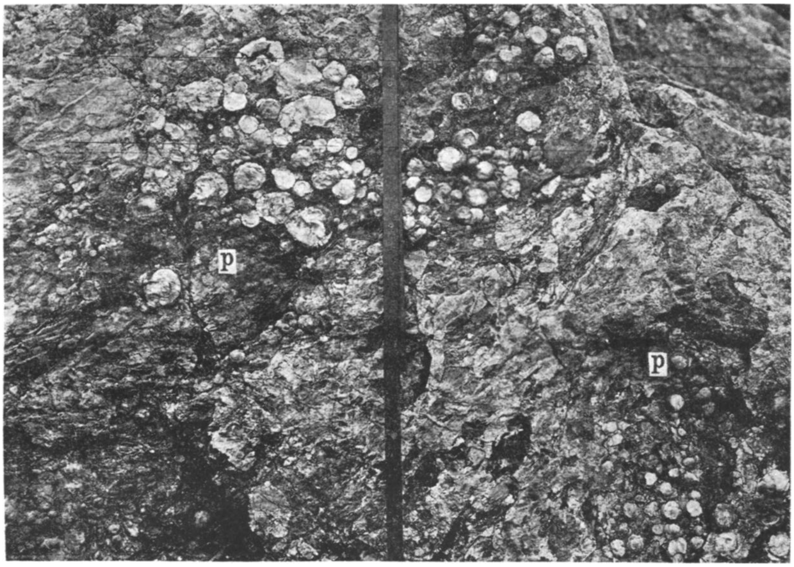


FIG. 4.—Pinite (*p*), replacing portions of the matrix of a spherulitic rhyolite

In the valley of Harbour Main Brook, among a series of rhyolite flows and tuffs, tuff beds up to 75 feet thick have been partially altered to pinite, and spherulitic rhyolite flows up to 30 feet thick are streaked and banded with pinite. These rocks have been prospected to depths of 15 and 20 feet, probably under the misapprehension that they carried pyrophyllite. A chemical analysis of the pinitized groundmass of the spherulitic rhyolite is given on p. 137 (No. 8).

CHEMICAL ANALYSES

Chemical analyses of eight typical rocks showing the various types and some of the stages of the alterations and replacements which have affected the volcanics are here given. These analyses were recalculated to correspond approximately to the mineral composition of the rocks. Small amounts of water of absorption, iron oxides except in No. 7, excess alumina, etc., have been lumped together as such under "other constituents." This involves of course a slight but inappreciable error in the proportions of the other minerals. It is probable that some sericite is also present in rocks Nos. 3 and 4, but owing to the difficulty of distinguishing sericite from pyrophyllite under the microscope, and because of the fact that the decrease in potash with an increase in water

TABLE I

SHOWING CHARACTER OF ALTERATIONS OF RHYOLITE

	1	2	3	4	5	6	7	8
SiO_2	76.24	80.60	74.51	72.10	65.04	88.09	54.47	61.07
Al_2O_3	13.94	11.27	17.12	21.51	29.49	9.53	27.14	22.99
Fe_2O_3	0.89	0.89	1.28	0.54	0.28	0.20	2.58	1.56
FeO	0.13	0.08	0.08	n.d.	n.d.	n.d.	0.47	0.42
MgO	0.27	0.31	0.04	0.04	0.04	0.05	2.44	0.65
CaO	1.07	0.66	0.13	0.49	0.10	0.58	0.81	1.63
Na_2O	2.55	1.16	0.48	0.42	0.33	n.d.	0.68	0.63
K_2O	4.95	4.68	3.68	2.21	0.33	n.d.	8.01	7.58
H_2O+	0.15	0.49	2.44	3.09	4.84	1.68	3.44	2.93
H_2O-	0.03	0.11	0.09	0.23	0.03	0.04	0.27	0.23
MnO	Trace	Trace	Trace	n.d.	n.d.	n.d.	0.09	0.17
	100.22	100.25	99.85	100.63	100.48	100.17	100.40	99.86
Sp. G.	2.64	2.64	2.73	2.77	2.83	2.70	2.82	2.70

1. Unaltered dark-gray flow rhyolite (228 *D* 1 *c*).
2. Silicified drab spherulitic rhyolite (228 *F* 2).
3. Pyrophyllitized rhyolite. Matrix of lenses; talc prospect 2 (228 *F* 3).
4. Pyrophyllitized rhyolite. Matrix of spherulite; talc prospect 1 (222 *E* 2 *j*).
5. Pyrophyllite. Light greenish-yellow waxy pyrophyllite from talc prospect 1 (222 *E* 2 *f*).
6. Quartz-pyrophyllite schist. Nodule in pyrophyllite (5); talc prospect 1 (222 *E* 2 *g*).
7. Pinite; dark dirty-green waxy, matrix of spherulitic rhyolite. Manuels (228 *D* 1 *h*).
8. Pinite schist. Matrix of spherulitic rhyolite, Harbour Main (232 *E* 2 *b*).

indicates that the replacing mineral is pyrophyllite, it has been calculated as that alone. Owing also to the liability of error involved in assigning the elements of the pinitic rocks to the correct minerals in the right proportions, only a rough estimate of their mineral composition is given. The iron oxides and magnesia of No. 7 must be present as an integral part of the white mica molecule, as no other mineral except quartz can be distinguished in thin section.

TABLE II

RECALCULATED ANALYSES

	Quartz	Orthoclase	Albite	Anorthite	Pyrophyllite	Other Constituents	White Mica
1......	39.6	29.4	21.4	5.2	....	4.4	....
2......	53.7	27.8	9.9	3.1	....	5.5	....
3......	28.3	21.7	4.2	0.6	43.6	1.6	....
4......	18.7	13.3	3.6	2.5	61.1	0.8	....
5......	1.3	....	....	....	91.8	1.6	5.3
6......	65.7	....	....	....	33.4	0.9	....
7......	Present	....	....	....	....	....	About 75 per cent
8......	Present	Present	Present	....	....	....	About 60 per cent

PETROGRAPHY

No. 1 (228 *D* 1 *c*). This specimen was taken near the top of a 50-foot banded reddish-gray felsite flow. In thin section the texture varies from microfelsitic to very minutely microcrystalline and the flow lines are marked by hematite dust. The flow lines are sharply curved and crenulated and several are replaced by quartz, especially in the loops of the curves, so that the rock analyzed as representing the composition of the original rhyolite only approximates such an unaltered condition.

No. 2 (228 *F* 2). This rock is a drab to fawn-colored microspherulitic rhyolite with secondary iron oxide in veinlets and specks. In thin section the groundmass is a finely microcrystalline aggregate of quartz and orthoclase, with fan-shaped microspherulitic areas. Secondary quartz is present as grains and lenses, as well as replacing portions of the spherulitic aggregates. A minute amount of sericite and quartz occurs along fractures.

No. 3 (228 *F* 3). This specimen, a pyrophyllitized rhyolite, was taken from the slightly sheared matrix surrounding lenses of white rhyolite (Fig. 2) adjacent to pyrophyllite veins at talc prospect 2. In thin section the rock shows as a microcrystalline aggregate of granular quartz and feldspar and of scales and fibers of pyrophyllite in about equal amounts.

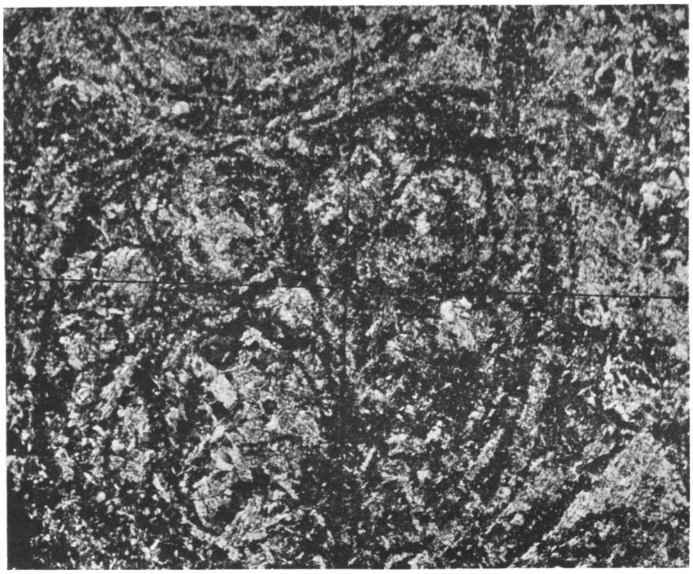


FIG. 5.—Perlitic structure preserved in pyrophyllitized rhyolite. Ordinary light, ×60.

No. 4 (222 *E* 2 *j*). This is the matrix, a pyrophyllitized rhyolite, in which a 6-inch spherulite was found essentially unaltered. In thin section the rock consists of an aggregate of very minute microscopic scales of pyrophyllite, complete except for a remarkably well-preserved perlitic structure, outlined by microcrystalline quartz with probably some orthoclase (Fig. 5). The rock is in a much more advanced stage of alteration to pyrophyllite than the preceding specimen.

No. 5 (222 *E* 2 *f*). Light greenish-yellow pyrophyllite with a fair cleavage. In thin section the rock is seen to be composed of a homogeneous felt of exceeding minute microscopic scales and fibers of pyrophyllite, with a strong tendency toward a very good alignment parallel to the cleavage in a section at right angles to it and with long, parallel, fibrous shreds in a section approximately parallel to the cleavage.

No. 6 (222 *E* 2 *g*). A white quartzose nodule or lense of quartz-pyrophyllite schist about 1 foot in diameter taken from a pyrophyllite vein at talc prospect 1. In thin section the rock presents what might be called a micro-blotchy groundmass composed of aggregates of either microcrystalline quartz or of scales of pyrophyllite. Some fibers of pyrophyllite also occur interstitially in the quartz areas.

No. 7 (228 *D* 1 *h*). This is the dark grayish-olive, waxy-lustered matrix of the spherulitic rhyolite illustrated in Fig. 4. In thin section the rock is seen to consist of an aggregate of extremely fine shreds and scales of white mica with lines of partially replaced microcrystalline quartz which are probably replacements of certain of the original rhyolite flow lines not yet entirely replaced by the white mica.

No. 8 (232 *E* 2 *b*). Grayish-olive pinite schist with small unaltered spherulites or spherulites partially replaced by quartz. In thin section the material appears as a perlitic microcrystalline groundmass of quartz and orthoclase partially replaced by sericite. The perlitic cracks are outlined by threads of sericite fibers, as illustrated in Fig. 6, and they often form the boundaries of serocitized areas which present the appearance of eyes, sometimes with a reticulating network of sericite veins connecting two adjacent eyes. Within the sericitic material, isolated microspherulites, clusters of microspherulites, and long axiolites are often preserved intact. A few phenocrysts of orthoclase are present and are remarkably fresh, although occasionally flecked with sericite. The secondary material consists of an aggregate of microscopic sericite scales and fibers associated with grains and areas of secondary quartz. Minerals originating through decomposition at the surface are completely absent except for a trace of iron oxides in the groundmass and a slight cloudiness in the feldspars, probably due to kaolin.

PRELIMINARY SILICIFICATION

The first process of alteration which operated on the Avondale Volcanics was that of regional silicification. On these preliminary silicified rocks a local series of alterations, those of pyrophyllitization, pinitization, and further local silicification, were superimposed.

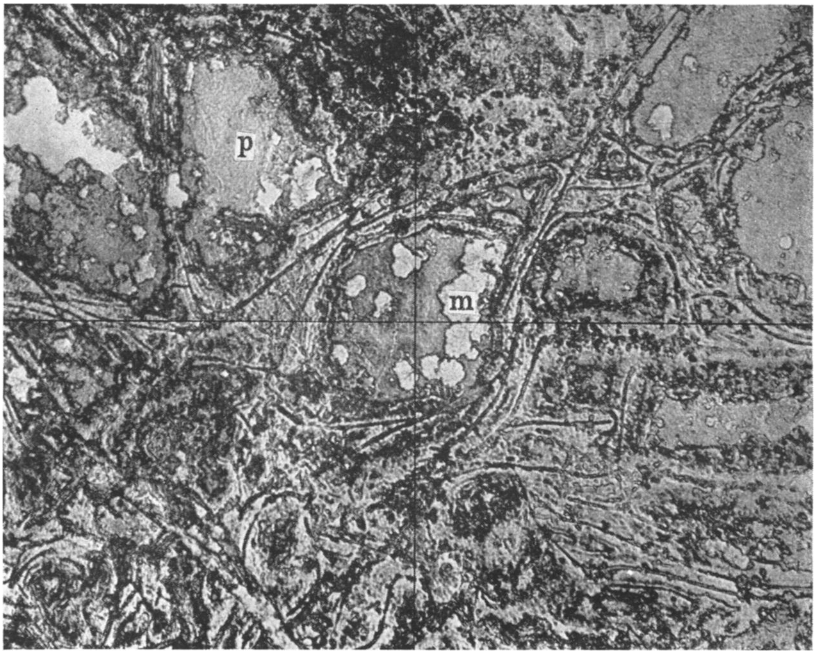


FIG. 6.—Perlitic structure preserved in pinitized rhyolite. Ordinary light, ×35. *m* = microspherulites; *p* = pinite.

This is evidenced by the following data: (1) few later quartz veins are found traversing the pinite, quartz schists, or pyrophyllite; (2) fragments of breccia in the volcanic breccias often exhibit quartz veins which stop abruptly at the contact with the matrix, and (3) under the microscope aggregates of sericite scales are found replacing granular quartz which had previously replaced the heart of a spherulite, and these sericite scales finger into and inclose unreplaced fragments of quartz, proving definitely their later origin.

The spherulitic rhyolites are the rocks which exhibit most clearly the manner in which the silicification has taken place. The silica here is present for the greater part as a milky-white chalcedonic quartz, but vitreous, granular, and white vein-like quartz as well as quartz crystals are common. The chalcedony usually forms the outer borders of the concentric crescent-shaped areas, and of the hearts of the replaced zones of the spherulites, while the inner portion may be recrystallized to form comb structure through the interlocking of quartz crystals, or little geodes with terminated crystals projecting into a small cavity, or granular vitreous quartz. When only one form of the silica is present it is very generally of a chalcedonic nature. It is interesting to note that while at Manuels it is the spherulites of the rhyolites which are most generally replaced, at Clarenville it was the groundmass which was replaced instead of the spherulites, because of the perlitic structure of the former offering the most favorable surfaces for attack. The banded rhyolites are often lined or streaked with quartz veins parallel to the planes of flow, which in some cases are a result of replacement and in others of vein filling. In thin section, lenses, lines, and granules of secondary quartz are found to be a common characteristic of the slightly silicified banded flows. Fig. 7 illustrates the preservation of the perlitic structure in the quartz which is replacing the groundmass of a spherulitic rhyolite from Clarenville. The perlitic cracks are outlined by sericite.

That the silicification of the rhyolites has been due to secondary metasomatic processes and is not a primary phenomenon is indicated by (1) the interruption of fluxion lines by the replacing quartz, (2) by the presence of unsupported fragments of unreplaced rhyolite in the quartz areas, and (3) by the preservation in the quartz of original structures of the rhyolite, such as the perlitic structure.

The first stage then in the alteration of these volcanics has consisted in the silicification under relatively static conditions by hot siliceous waters of rhyolite flows which may be represented as having had a similar chemical composition to the present relatively unaltered gray felsites. Analysis No. 1 may be taken as the composition of the original rock from which the silicified rhyolite represented by analysis No. 2 has been derived.

Chemically this has resulted in a decrease in the percentages of potash, soda, lime, and alumina, an increase in the percentage of silica, and a relative decrease in the percentage of sodium with respect to potassium. The process operated through the replacement of the feldspars by quartz and a relatively more rapid replacement of the soda feldspars than of the potash feldspars. The solutions which effected this alteration doubtless belonged to the same general period of volcanic activity as the extrusion of the lavas themselves.

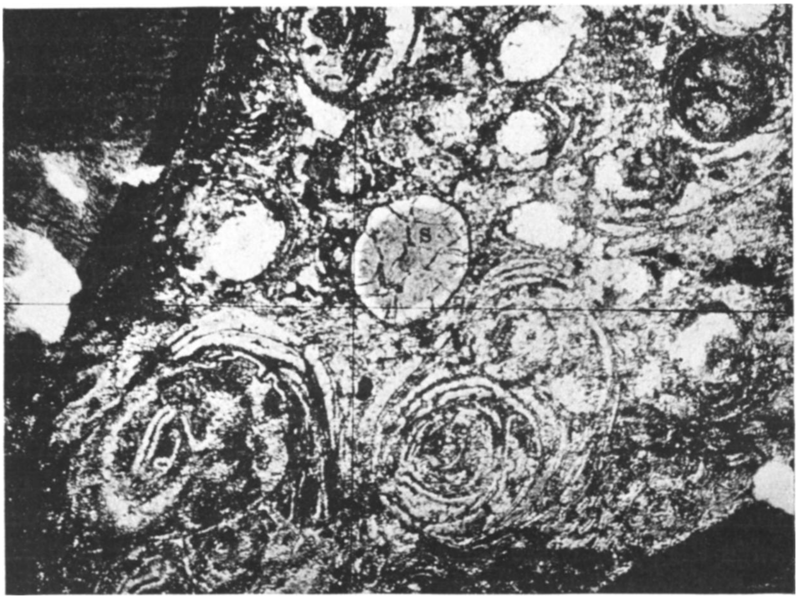


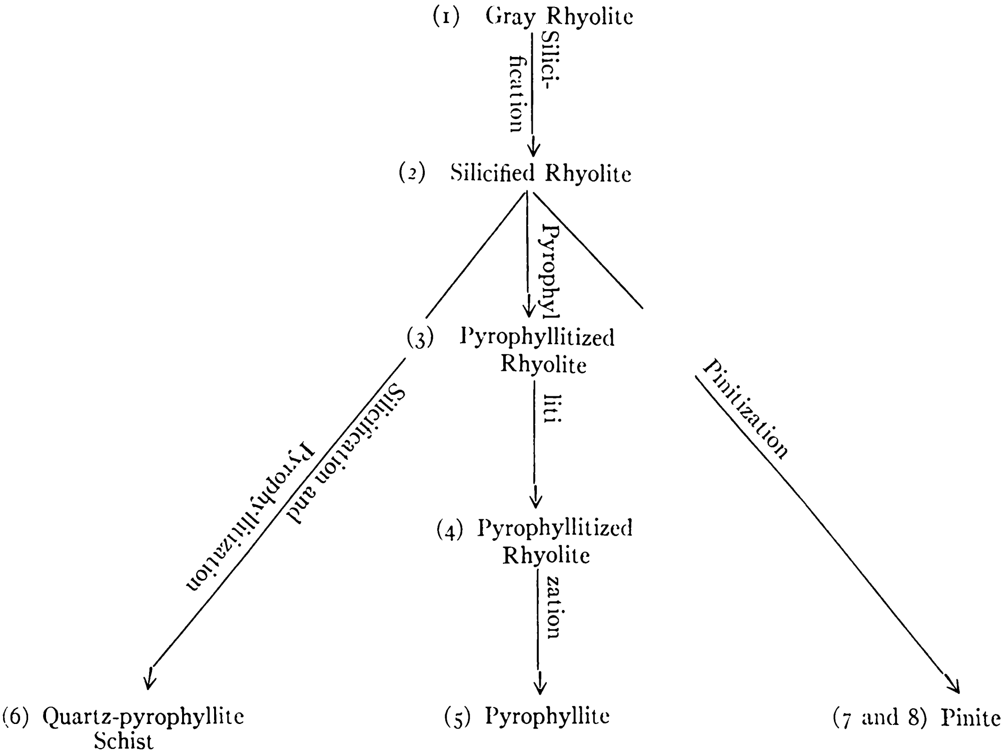
FIG. 7.—Perlitic structure preserved in quartz replacing the groundmass of a spherulitic rhyolite. Ordinary light, ×35. *s* = spherulite.

PYROPHYLLITIZATION, PINITIZATION, AND SILICIFICATION

As has been remarked before, a later series of local alteration processes has been superimposed on the already widespread slightly silicified volcanics. The origins of the pyrophyllite, the pinite, and the quartz-pyrophyllite or quartz schists are so intimately interwoven that all may be treated together.

The proof that these rocks have originated through replacement is based on the following data: (1) the preservation of the structures of the primary rock in the secondary rock, (2) the presence of unattached and unsupported portions of the country rock within the replacement products, (3) the introduction of large quantities of some elements and the solution of others without any notable change in volume or porosity, (4) gradational contacts, and (5) the massive homogeneity of all the rocks, and especially of the pyrophyllite, which does not show the foliated crystalline structure so characteristic of pyrophyllite veins which fill preexisting fractures. To quote examples which belong to the first category, we find the following structures preserved in pyrophyllitized rhyolite: (1) flow structure, (2) spherulites, (3) pebbles of a partially replaced conglomerate, and (4) perlitic structure (Fig. 5); these in the quartz-pyrophyllite rocks: (1) spherulites and (2) breccia structure; the following in pyrophyllite: (1) fragments of volcanic breccias, (2) pebbles of conglomerates, and (3) spherulites; while in the pinite and pinite schists we have preserved spherulites, traces of flow structure, axiolites, microspherulites, and perlitic structure (Fig. 6). Additional evidence of replacement is found in the inclusions and stringers of country rock within the pyrophyllite veins and the intimate manner in which the two are often intermixed. Not only this most convincing field evidence but chemical considerations prove almost conclusively that these rocks must have originated through replacement of rhyolite or rhyolitic volcanics.

From a study of the foregoing field and chemical evidence, conclusions have been drawn as to the genetic relationships of the eight different rocks described under "Chemical Analyses" and "Petrography," and as to the succession of processes which produced them. This relationship is graphically represented by the following diagram, in which the numbers refer to the chemical analyses given under "Chemical Analyses," which may be taken as typifying the composition of the respective rocks:


(1) Gray Rhyolite
Silicification
(2) Silicified Rhyolite
Pyrophylliti-zation
(3) Pyrophyllitized Rhyolite
(4) Pyrophyllitized Rhyolite
Silicification and Pyrophyllitization
Pinitization
(6) Quartz-pyrophyllite Schist
(5) Pyrophyllite
(7 and 8) Pinite

TEMPERATURE OF FORMATION OF PYROPHYLLITE

Clapp (1914, 120) assumes that alunite and pyrophyllite are probably developed only under moderate conditions of pressure and temperature such as exist near the surface. Although this is a common mode of origin for both alunite and pyrophyllite, it is certainly not the only set of conditions under which the latter forms.

For instance, pyrophyllite is noted by Dana (1909) as a mineral often forming the base of schists and gneisses, and by Lacroix (1895) as a mineral of the crystalline schists and Paleozoic metamorphics.

Artificially, K. von Chrustchoff (1894) obtained what he believed to be pyrophyllite by heating gelatinous silica, gelatinous alumina, and gelatinous zirconium hydrate in a platinum tube at increasing temperature for six days. The product obtained was a zirconia-bearing pyrophyllite. Its specific gravity was 2.87 and it appeared in thin hexagonal plates, which he states are not true hexagonal plates unless there be optical anomalies.

SiO_2	Al_2O_3	ZrO_2	H_2O	Total
53.65	23.76	14.54	7.86	99.81

Le Chatelier (1887) determined the points at which pyrophyllite loses its water by noting the points at which the temperature remained constant with absorption of heat and found two such points, the first at 700° and the second at 850°.

From the foregoing data it is evident that pyrophyllite is a mineral which may form under conditions varying from the high temperatures of dynamic metamorphism to the near-surface temperatures and pressures of solfataric agencies.

TEMPERATURE OF FORMATION OF PINITE

Pinite, if considered as an impure sericite, as suggested by Clarke (1911), has a varied range of conditions under which it may form. Clarke states, however, that "the alteration [to sericite] is most conspicuous in regions where dynamic metamorphism has been most intense, high temperature, the chemical activity of water and mechanical stress all working together to bring it about."

A green micaceous mineral described as mariposite by Silliman, and whose composition, shown by two analyses, as suggested by Hillebrand (1895), resembles pinite, is characteristic of the mother lode in Tuolumne and Mariposa counties, California.

Crosby (1880) describes pinite as a product of surface decomposition of petrosilex and felsites in the vicinity of Boston, Massachusetts. Bell (1887) found it at Ballater Pass interspersed through granitic rocks and along their joint planes, and ascribes its origin to the decomposition or alteration of orthoclase feldspar, an intermediate stage in its conversion into kaolin.

Cole (1886) describes pinite occurring as an alteration product of spherulitic rhyolites, in conjunction with silicified spherulites. He suggests that thermal waters are responsible for the origin of both the pinite and quartz.

From these references it is evident either that there is a difference of opinion as to the conditions under which pinite forms, or that it is stable under widely variant temperatures and pressures. It is probable, however, that it demands higher temperatures and pressures than exist at the surface as conditions for its most favorable development, and such is doubtless the case with respect to the pinite of Conception Bay.

ALTERNATIVE DEVELOPMENT OF PINITE OR PYROPHYLLITE

Since sericite or pinite is the usual product of hydrothermal alteration it is pertinent to inquire if any reason can be found why in certain cases pyrophyllite should be the product formed. A possible equation (1) representing the formation of sericite from orthoclase is quoted from Clarke (1911), and a similar possible equation (2) representing the formation of pyrophyllite from orthoclase is given below:

$$(1)\quad 6\ \mathrm{KAlSi_3O_8+2H_2O \leftrightarrows \underset{(sericite)}{2KH_2Al_3Si_3O12}+2K_2SiO_3+10SiO_2}$$

$$(2)\quad 6\ \mathrm{KAlSi_3O_8+3H_2O \leftrightarrows \underset{(pyrophyllite)}{6HAlSi_2O_6}+3K_2SiO+3SiO_2}$$

From these equations three factors are suggested as the possible elements influencing the alternative development of sericite and pyrophyllite: (1) the effectiveness of hydrolysis, (2) the mass action of the excess silica in solution, and (3) the mass-action effect of excess potash in solution. The dominance of the first two factors would be conducive to the formation of pyrophyllite, and the dominance of the third factor would be favorable to the production of sericite. This may be illustrated more graphically, without however implying anything as to the actual mode of operation, by writing the equation for the formation of pyrophyllite from sericite as a balanced reaction:

$$\mathrm{\underset{(sericite)}{2KH_2Al_3Si_3O_{12}}+6SiO_2+H_2O \leftrightarrows \underset{(pyrophyllite)}{6HAlSi_2O_6}+K_2SiO_3}$$

If now the quantity of silica is present in the solution in large enough excess and the effectiveness of hydrolysis is relatively stronger, the reaction will produce pyrophyllite:

$$\underset{\text{(sericite)}}{2KH_2Al_3Si_3O_{12}}+6SiO_2+H_2O \rightarrow \underset{\text{(pyrophyllite)}}{6HAlSi_2O_6}+K_2SiO_3$$

while if K_2SiO_3 or potash in some other form is present in large enough quantity the alternative reaction will take place and sericite will be produced:

$$\underset{\text{(pyrophyllite)}}{6HAlSi_2O_6}+K_2SiO_3 \rightarrow \underset{\text{(sericite)}}{2KH_2Al_3Si_3O_{12}}+6SiO_2+H_2O$$

CHEMICAL PHENOMENA CONNECTED WITH ORIGIN OF PYROPHYLLITE

From a comparison of the analysis (No. 2) of the silicified rhyolite with that of the pyrophyllite (No. 5), it will be seen that the change in composition has been such as might have been brought about essentially through three processes: (1) the introduction of alumina, (2) the replacement of the alkalies by hydroxyl, and (3) the solution of silica. The analyses 2, 3, 4, and 5, recalculated into their mineral composition, show a direct transition from the country rock (the silicified rhyolite) into pyrophyllite through a decrease in the quantity of quartz, feldspars, and impurities and a simultaneous increase in the content of pyrophyllite. In order that the original rock may be so altered as to give the mineral analyses shown by the transitional rocks, it is necessary that metasomatic replacement of both the quartz and the feldspars should have proceeded synchronously and at a much faster rate with respect to the quartz than with respect to the feldspars. This process would involve the introduction of large amounts of alumina, the gradual replacement of the alkalies by hydroxyl at a more rapid rate in the case of the soda than of the potash, and the solution of portions of both the silica existing in combination with other elements in the rock and that present as free quartz.

The heterogeneous, blotchy character of the quartz-pyrophyllite rock when seen in thin section suggests that the rock may have been in the condition of a more or less homogeneous glass when acted upon by the silicifying and pyrophyllitizing solutions, in view of the fact that its chemical composition and mineral arrangement would involve the simultaneous replacement of the feldspars of a crystalline rock by silica and pyrophyllite, and of its quartz by pyrophyllite.

ORIGIN OF PINITE AT MANUELS

From a further study of the chemical analyses, it becomes evident that while the silicified rhyolites, pyrophyllitized rhyolites, and pyrophyllite have all decreased in their content of iron, magnesium, potassium, and soda, the pinite analysis (7) shows a decided increase in the first three of these elements. During the formation of pyrophyllite vast quantities of potash must have been liberated and carried in solution in the circulating waters. Is it not possible that away from the main channels these waters deposited their load as pinitic replacements of the rhyolite under the control of lower temperatures and pressures and the mass-action effects of the excess potash in solution? It seems reasonable to suppose that the pinite here was an essentially contemporaneous formation with the quartz-pyrophyllite schists and pyrophyllite, receiving some of the magnesia, potash, and iron released by the formation of the pyrophyllite, as the quartz schists have received some of the silica originating at the same time.

ORIGIN OF THE PINITE SCHIST AT HARBOUR MAIN

The chemical analysis of the pinite schist recalculated for sericite gives the rock a mineral composition of about $\frac{3}{5}$ sericite and $\frac{2}{5}$ quartz, feldspar, and other constituents. Examination of thin sections shows that this result has been brought about through the replacement of both the feldspar and quartz by sericite. If we consider the rock previous to pinitization to have had the composition of the silicified rhyolite (No. 2), then the process cited involves the substitution of potash for soda in the feldspars, the addition of potash and alumina, and the subtraction of silica and soda.

There is considerable evidence that this rock was not formed at the surface. There are no secondary products of decomposition, such as kaolin or limonite, associated with the pinite. It occurs in quantity only in certain zones and extends to a considerable depth, as exposed in a prospect pit for talc, south of Harbour Main.

Where it occurs as patches or specks it bears no apparent relation to the surface. Furthermore, the pinitic material has undergone dynamic metamorphism and is sheared and cleaved, while chemically its origin involves the introduction of alumina and potash through replacement.

GENERAL OBSERVATIONS

It is quite probable that the foregoing processes operated under conditions of some dynamic movement, as their characteristic development is along shear zones, and their products assume a lenticular structure which is as characteristic of the minuter structures of the rocks as of the veins themselves. Moreover, the rocks themselves have been sheared and possess a more or less prevalent cleavage, conditioned by the growth of their constituent minerals in more or less parallel arrangement.

It is probable that the factors determining which of these three rocks—pyrophyllite, pinite, and quartz-pyrophyllite—shall form are to be found in the temperature, pressure, and chemical content of the solutions themselves, in the relative effectiveness of hydrolysis, and in the mass-action effects of the compounds in solution.

The concentration of the potash in the pinite, and the silica in the quartz-pyrophyllite rocks may be accounted for on the theory of a redistribution of the elements, but the tremendous contributions of alumina represented by the pyrophyllite, and to a minor extent by the pinite, must be accounted for otherwise. The close connection between the pyrophyllite deposits and the granite-Avondale Volcanics contact south of Manuels and between the pinitized rhyolites and the Woodfords monzonite stock is hence of significance. It may be that there is no genetic connection between these minerals and the intrusives, and that their formation was entirely dependent on the locus of fault zones in those localities. But there are numerous other profound fault and shear zones in this area with no exceptional alterations.

Hence it seems probable that when faulting took place between the volcanics and the intrusive granite or monzonite, the still hot magmatic waters were released and found their way upward along these fault zones, either contributing the alumina directly, or perhaps indirectly through mingling with already aluminous solutions. Such solutions, if present, would be those which had accomplished the silicification of the volcanics with their attendant solution of alumina under static conditions and hence before the period of orogenic movement, which folded the volcanics and witnessed the intrusion of the plutonic batholith and stock. The evidence bearing on the exact dates of the periods of faulting and folding, however, is not conclusive.

COMPARISONS WITH OTHER DEPOSITS

Comparisons with other deposits show that, according to the descriptions, the pyrophyllite deposits of the Pambula goldfield, New South Wales, and of Chatham and Moore counties, North Carolina, are essentially similar to those in Newfoundland, and it is here suggested that possibly they have had a similar origin.

Clapp (1914) described quartz-pyrophyllite rocks from Kyuquot Sound, Vancouver Island, which may be taken as a type of pyrophyllite deposits developed by solfataric agencies under conditions of temperature and pressure existing near the surface; while those of Newfoundland are a type originating under intermediate conditions of temperature and pressure.

In the first case the pyrophyllite rocks are associated with alunite and in the latter case with pinite. In the Kyuquot deposits the original quartz of the replaced dacite has not suffered any loss except in one doubtful case, while the distinctive feature of the Newfoundland rocks has been the replacement of quartz in rhyolites by pyrophyllite.

The two deposits are similar in that, in both cases, the rocks are associated with intrusive batholiths, the one with a feldspathic quartz diorite and the other with granite. Both are metasomatic replacements of acid volcanics, while in the zone of alteration there seems to have been some transfer of material, and soda, lime, magnesia, and iron oxides have been lost in each case.

CONCLUSION

From the foregoing evidence the conclusion may be drawn that: the pyrophyllite, pinite, and quartz-pyrophyllite schists of the

Avondale Volcanics owe their formation to metasomatic replacement and alteration of previously silicified rhyolites or rhyolitic volcanics by thermal waters, under conditions of dynamic stress and intermediate temperatures and pressures, operating along channels primarily determined by fault or shear zones. Chemically, the salient features of these alterations have been the introduction of alumina, the more or less complete substitution of the hydroxyl element in place of the alkalies, and the solution of soda. The solutions instrumental in causing these alterations may have been to a greater or less extent juvenile waters emanating from the intrusive granite batholith and monzonite stock at some period subsequent to the time of their injection.

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BIBLIOGRAPHY

Bell, W. H. "New Localities for the Mineral Agalmatolite with Notes on Its Composition," *Miner. Mag.*, VII (1887), 28.

Chrustchoff, von K. "Artificial Zircons," abstract in *Miner. Mag.*, X (1894), 259.

Clapp, C. H. "The Geology of the Alunite and Pyrophyllite Rocks of Kyuquot Sound, Vancouver Island," *Summary Rept. of the Geol. Surv., Dept. of Mines, for 1913* (1914), pp. 109–26.

Clarke, F. W. "Data of Geochemistry," *U.S. Geol. Surv., Bull. 491* (1911), p. 567.

Cole, G. A. J. "On the Alteration of Coarsely Spherulitic Rocks," *Quart. Jour. Geol. Soc.*, XLII (1886), 186–87.

Crosby, W. O. "Pinite in Eastern Massachusetts, Its Origin and Geologic Relations," *Am. Jour. Sci.*, 19 (1880), 116.

Dana, E. S. *A System of Mineralogy* (1909), p. 691.

Hillebrand, W. F. Quoted by H. W. Turner (1895).

Howley, J. P. Geologic Map of Newfoundland (1907).

Lacroix, A. *Minéralogie de la France* (1895), I, 471.

Le Chatelier, M. H. "De l'Action de la chaleur sur les argiles," *Bull. Soc. Min. France*, X (1887), 207.

Powers, F. D. "The Pambula Gold Deposits," *Quart. Jour. Geol. Soc.*, XLIX (1893), 233–35.

Pratt, J. H. "Talc and Pyrophyllite Deposits in North Carolina," *N.C. Geol. Surv., 1900, Economic Paper No. 3*, pp. 23–29.

Turner, H. W. "Further Contributions to the Geology of the Sierra Nevada," *U.S. Geol. Surv., 17th Ann. Rept.*, 1895. Part 1, p. 529.